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Kang et al.

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(54) METHOD AND APPARATUS FOR WAVE ENERGY CONVERSION

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(51) **Int. Cl.**

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F03B 13/18	(2006.01)
F03B 13/20	(2006.01)
F03B 15/00	(2006.01)

(52) **U.S. Cl.**
CPC ***F03B 13/1845*** (2013.01); ***F03B 11/063*** (2013.01); ***F03B 13/20*** (2013.01); ***F03B 15/00*** (2013.01); *F05B 2220/707* (2013.01); *F05B 2240/40* (2013.01); *F05B 2250/11* (2013.01); *F05B 2250/132* (2013.01); *F05B 2250/231* (2013.01); *F05B 2270/20* (2013.01); *Y02E 10/38* (2013.01)

(58) **Field of Classification Search**
USPC 290/42, 53; 65/500; 417/330–339; 60/500
See application file for complete search history.

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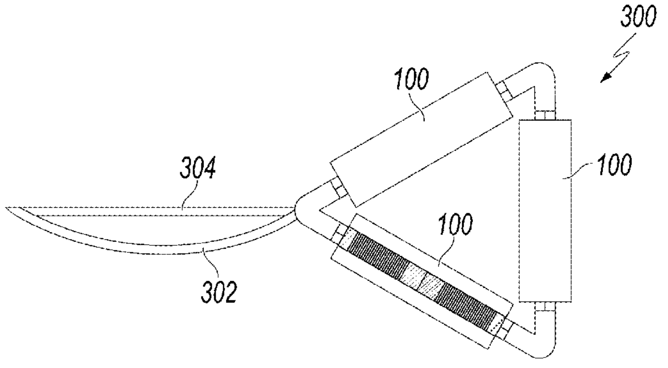
(57) ABSTRACT

A wave energy conversion cylinder includes an outer cylinder and a center rod disposed along an axis of the outer cylinder. A plurality of electrically-conductive windings are disposed about an inner circumference of the outer cylinder. A magnet is slidably disposed on the center rod. A buoyancy cylinder is disposed outwardly of the outer cylinder. A first moveable ring weight may be slidably disposed along the axis of the center rod and a second moveable ring weight may be slidably disposed along the axis of the center rod. The first moveable ring weight and the second moveable ring weight facilitate control to tune a mass moment of inertia of the wave energy conversion cylinder.

19 Claims, 5 Drawing Sheets



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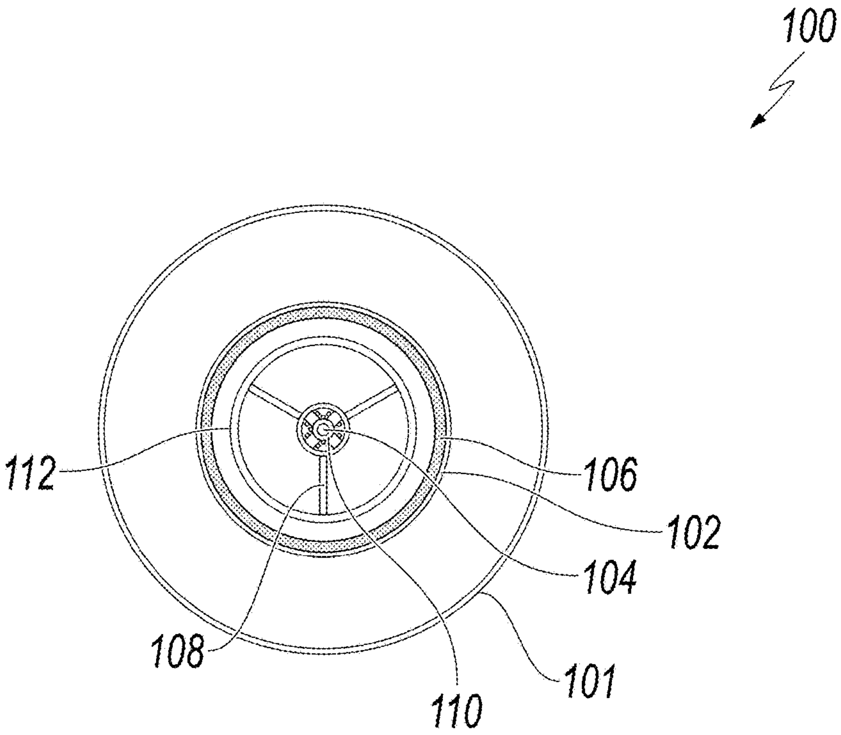


FIG. 1

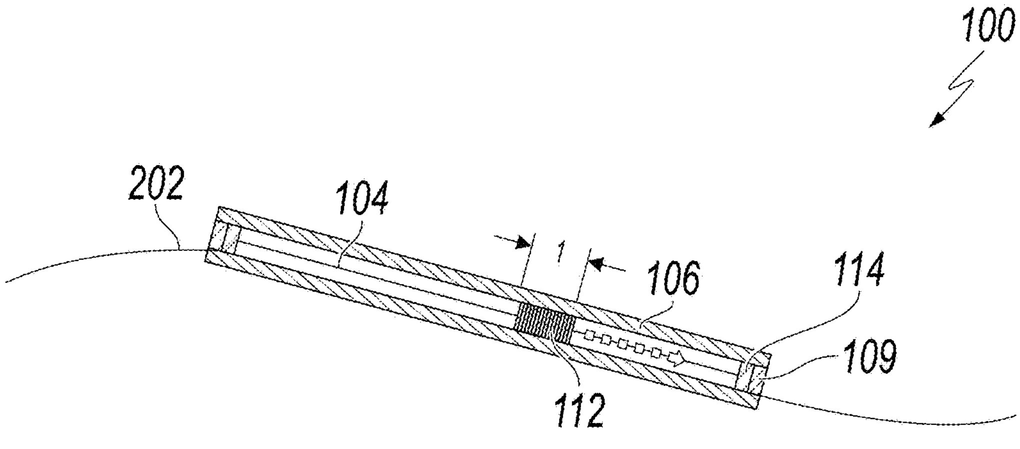
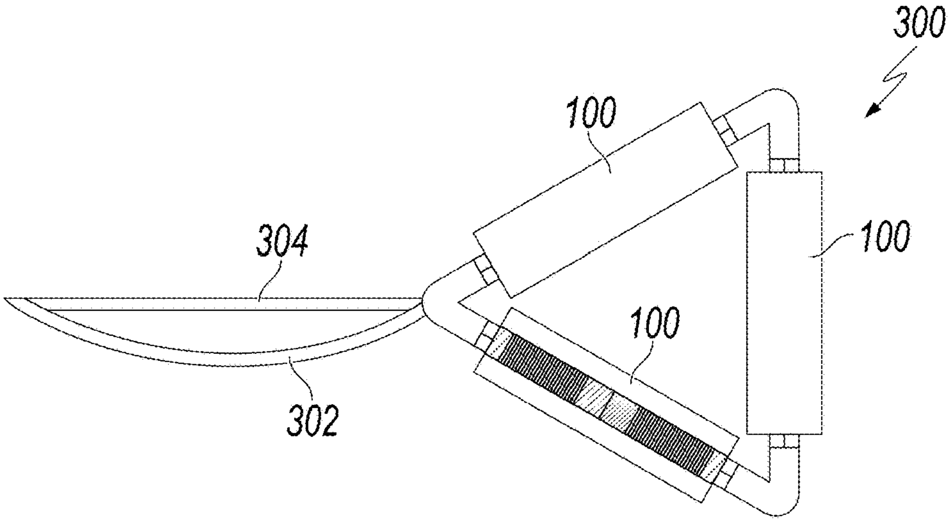


FIG. 2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304
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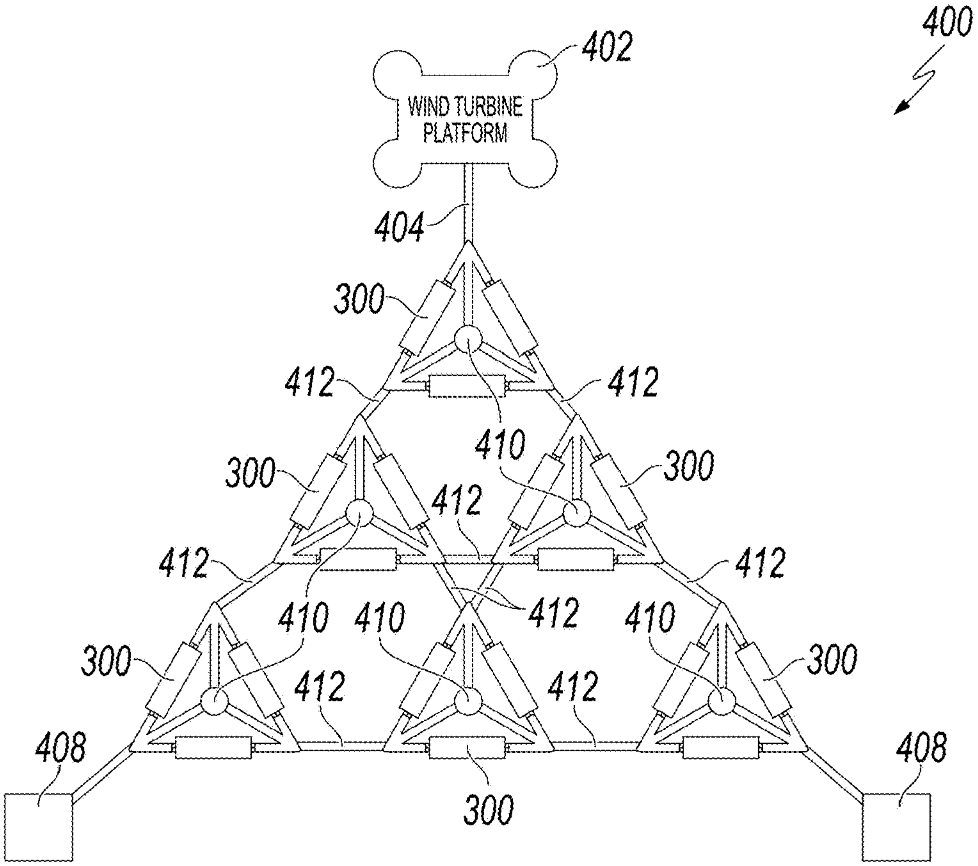
302

FIG. 3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WIND TURBINE PLATFORM
404
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412
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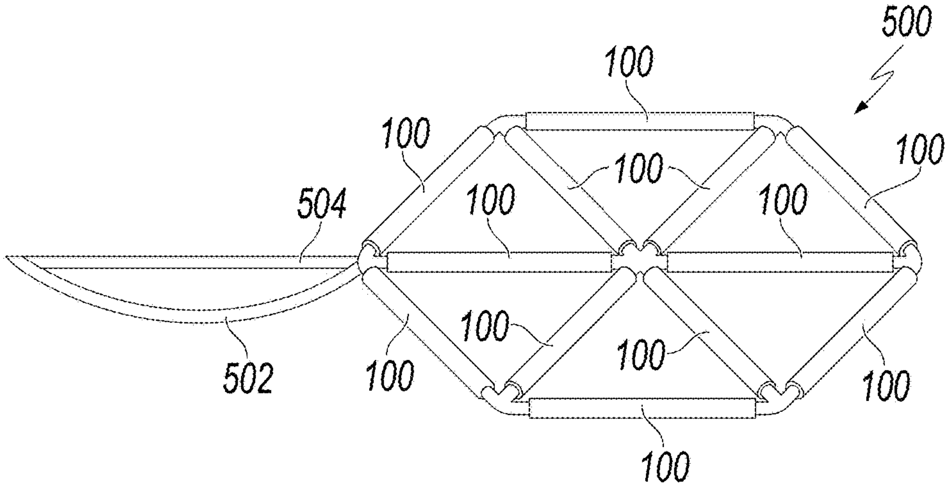
412
300
408
408
300

FIG. 4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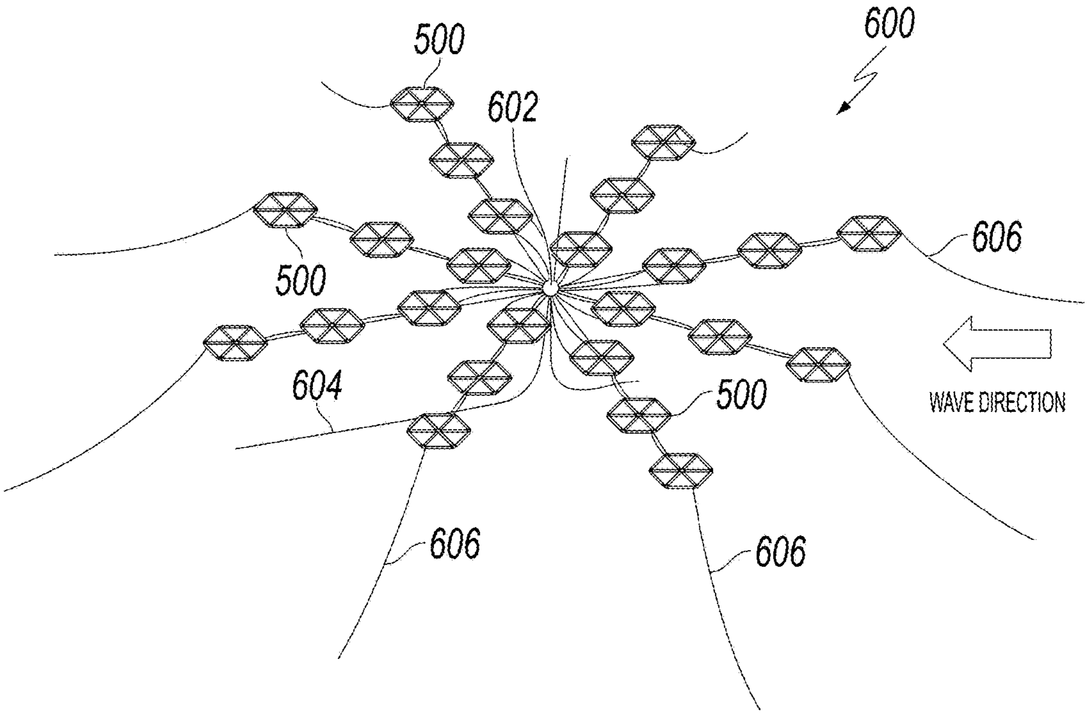
502
100
100
100

FIG. 5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602
500
606
500
604
500
WAVE DIRECTION
606
606

FIG. 6

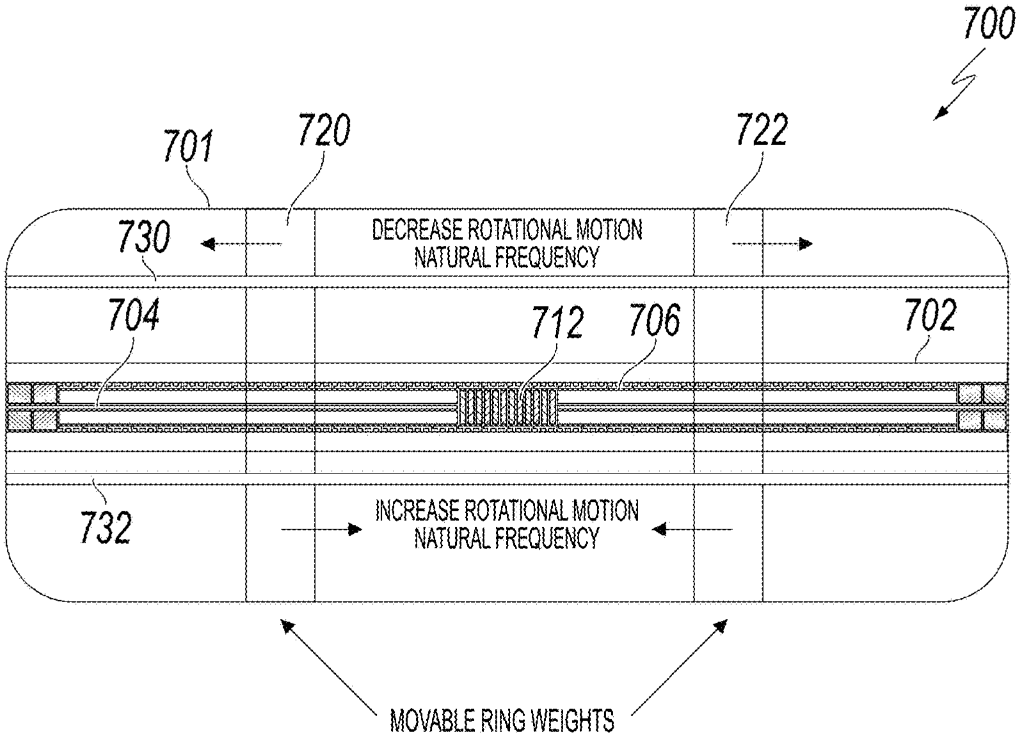
700
701
720
722
730
DECREASE ROTATIONAL MOTION NATURAL FREQUENCY
704
712
706
702
732
INCREASE ROTATIONAL MOTION NATURAL FREQUENCY
MOVABLE RING WEIGHTS

FIG. 7

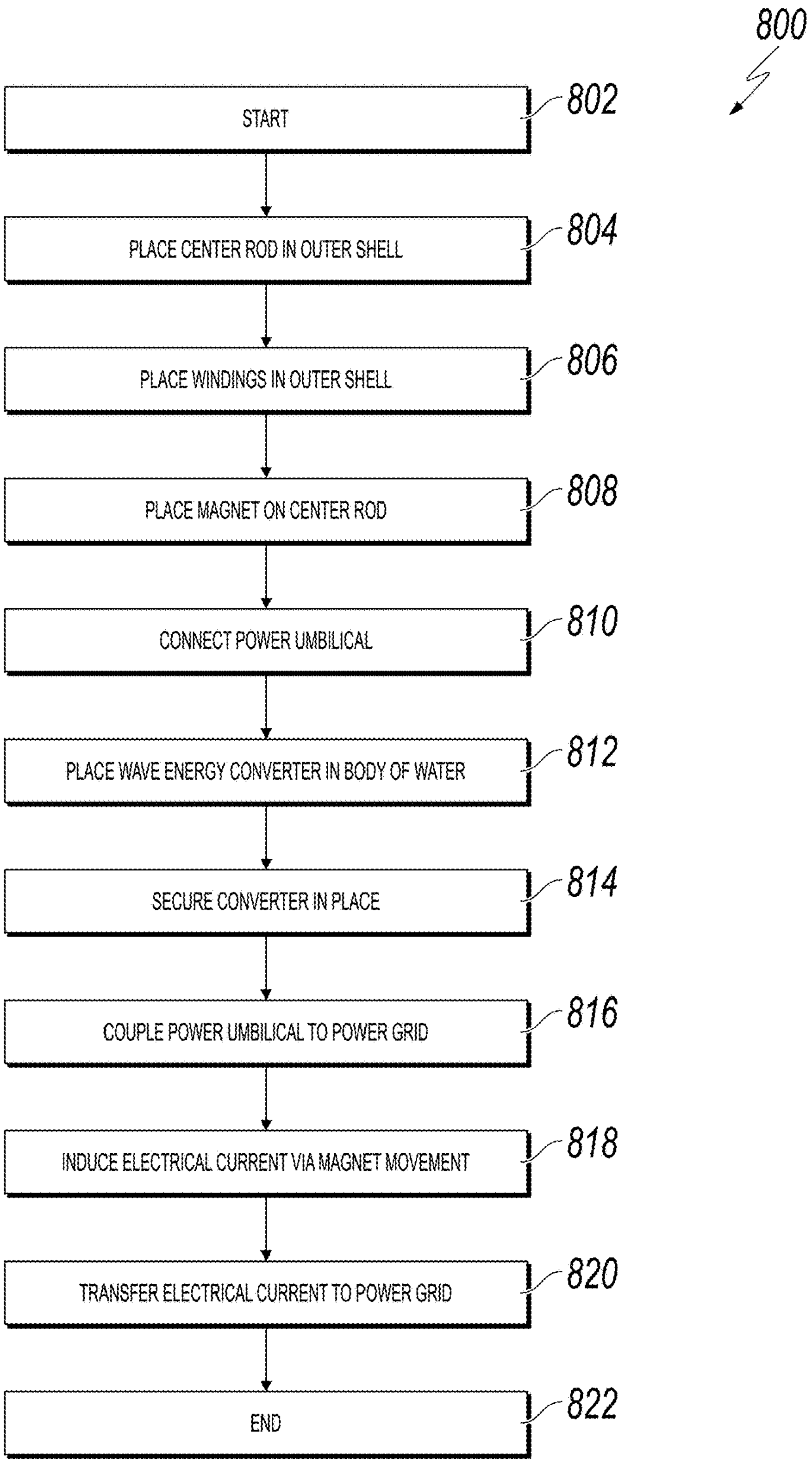
800
START
802
PLACE CENTER ROD IN OUTER SHELL
804
PLACE WINDINGS IN OUTER SHELL
806
PLACE MAGNET ON CENTER ROD
808
CONNECT POWER UMBILICAL
810
PLACE WAVE ENERGY CONVERTER IN BODY OF WATER
812
SECURE CONVERTER IN PLACE
814
COUPLE POWER UMBILICAL TO POWER GRID
816
INDUCE ELECTRICAL CURRENT VIA MAGNET MOVEMENT
818
TRANSFER ELECTRICAL CURRENT TO POWER GRID
820
END
822

FIG. 8

METHOD AND APPARATUS FOR WAVE ENERGY CONVERSION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to, and incorporates by reference the entire disclosure of, U.S. Provisional Patent Application No. 62/458,884, filed on Feb. 14, 2017.

TECHNICAL FIELD

The present disclosure relates generally to power conversion and more particularly, but not by way of limitation, to power conversion utilizing a surface-riding wave energy converter.

BACKGROUND

This section provides background information to facilitate a better understanding of the various aspects of the disclosure. It should be understood that the statements in this section of this document are to be read in this light, and not as admissions of prior art.

As worldwide energy demands increase, the need for cost-efficient, renewable sources of energy also increases. Such need has given rise to the development of solar, wind, geothermal, and other renewable sources of energy. One area of particular interest is the use of ocean wave energy for power conversion. Previous developments in wave-energy power conversion have utilized devices such as subsea turbines and large-draft devices. These devices are often plagued by high installation and maintenance costs thereby rendering them unsuitable as long-term sources of electrical power. Thus a need exists for a costs-efficient wave-energy conversion device.

SUMMARY

This summary is provided to introduce a selection of concepts that are further described below in the Detailed Description. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it to be used as an aid in limiting the scope of the claimed subject matter.

In one aspect, the present disclosure relates to a wave energy conversion cylinder. The wave energy conversion cylinder includes an outer cylinder and a center rod disposed along an axis of the outer cylinder. A plurality of electrically-conductive windings are disposed about an inner circumference of the outer cylinder. A magnet is slidably disposed on the center rod and a buoyancy shell is disposed outwardly of the outer cylinder.

In another aspect, embodiments of the present disclosure relate to a wave-energy conversion farm. The wave energy conversion farm includes at least one wave energy conversion device. The at least one wave energy conversion device includes at least one wave energy conversion cylinder. The at least one wave energy conversion cylinder includes an outer cylinder and a center rod disposed along an axis of the outer cylinder. A plurality of electrically-conductive coils are disposed about an inner circumference of the outer cylinder. A magnet is slidably disposed on the center rod. A buoyancy shell is disposed outwardly of the outer cylinder. An umbilical is electrically coupled to the plurality of electrically-conductive windings and electrically coupled to a power grid.

In another aspect, the present disclosure relates to a method of converting wave energy. The method includes providing a wave energy conversion cylinder. The wave energy conversion cylinder includes an outer cylinder and a center rod disposed along an axis of the outer cylinder. A plurality of electrically-conductive coils are disposed about an inner circumference of the outer cylinder. A magnet is slidably disposed on the center rod and a buoyancy cylinder is disposed outwardly of the outer cylinder. The method may also include connecting the plurality of electrically-conductive windings to a power grid, subjecting the wave energy conversion cylinder to wave action on a body of water, and inducing an electrical current in the plurality of electrically-conductive windings responsive to movement of the magnet.

BRIEF DESCRIPTION OF THE DRAWINGS

The disclosure is best understood from the following detailed description when read with the accompanying figures. It is emphasized that, in accordance with standard practice in the industry, various figures are not drawn to scale. In fact, the dimensions of various features may be arbitrarily increased or reduced for clarity of discussion:

FIG. **1** is a lateral cross-sectional view of a wave energy conversion cylinder in accordance with an exemplary embodiment;

FIG. **2** is a longitudinal sectional view of a wave energy conversion cylinder in accordance with an exemplary embodiment;

FIG. **3** is a top view of a delta surface riding wave energy converter in accordance with an exemplary embodiment;

FIG. **4** is a top view of a delta surface riding wave energy conversion farm in accordance with an exemplary embodiment;

FIG. **5** is a top view of a hexagonal surface riding wave energy converter in accordance with an exemplary embodiment;

FIG. **6** is a top view of a surface riding wave energy conversion farm in accordance with an exemplary embodiment;

FIG. **7** is a plan view of a tunable wave energy conversion cylinder in accordance with an exemplary embodiment; and

FIG. **8** is a flow diagram of a method for converting wave energy in accordance with an exemplary embodiment.

DETAILED DESCRIPTION

Various embodiments will now be described more fully with reference to the accompanying drawings. The disclosure may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein.

FIG. **1** is a lateral cross sectional view of a wave energy conversion cylinder **100**. The wave energy conversion cylinder **100** includes an outer shell **102** and a center rod **104** disposed approximately along a length of a long axis of the outer shell **102**. A buoyancy shell **101** is disposed around the outer shell. In a typical embodiment, the buoyancy shell creates an air gap between the outer shell **102** and the buoyancy shell **101** so as to increase the buoyancy of the wave energy conversion cylinder **100**. In various embodiments, a buoyancy foam can also be utilized as an alternative to an air-filled buoyancy shell. A plurality of electrically conductive windings **106** are formed about an inner circumference of the outer shell **102**. In a typical embodiment, the plurality of electrically conductive windings **106** are formed from a metallic material such as, for example, copper, aluminum, or steel; however, in other embodiments, any electrically conductive material could be utilized as dictated by design requirements. In a typical embodiment, the wave energy conversion cylinder **100** has a length of approximately 3.5 meters to approximately 10 meters; however, the length of the wave energy conversion cylinder **100** can be optimized for specific sea conditions.

Still referring to FIG. **1**, a bracket **108** is disposed on the center rod **104** and is movable along the center rod **104** from one end to the other. A plurality of bearing devices **110** are disposed between the bracket **108** and the center rod **104** so as to reduce friction between the bracket **108** and the center rod **104**. The bearing devices **110** are illustrated in FIG. **1** as ball rollers; however, in other embodiments, the bearing devices **110** could be any type of bearing as dictated by design requirements. A magnet **112** is disposed on an outer surface of the bracket **108** such that the plurality of electrically conductive windings **106** are exposed to a magnetic field produced by the magnet **112**. In a typical embodiment, the magnet **112** is a permanent magnet; however, in other embodiments, various types of magnets such as, for example electromagnets could be utilized as dictated by design requirements.

FIG. **2** is a longitudinal cross sectional view of the wave energy conversion cylinder **100**. The plurality of electrically conductive windings **106** are coupled to a cable box **109**. In a typical embodiment, the cable box **109** facilitates coupling of the wave energy conversion cylinder **100** to an electrical grid. In other embodiments, the cable box **109** can be an intermediate connection between the wave energy conversion cylinder **100** and the electrical grid. An absorber block **114** is disposed at each end of the wave energy conversion cylinder **100**. In a typical embodiment, the absorber block **114** is constructed of, for example, rubber or a spring and serves to dampen motion of the bracket **108** and the magnet **112** when the bracket **108** and the magnet **112** reach an end of the wave energy conversion cylinder **100**. The wave energy conversion cylinder **100** floats with low draft on a surface of water **202**. In a typical embodiment, the wave energy conversion cylinder **100** has a draft of approximately 70% of a radius of the wave energy conversion cylinder **100**. Such low draft exhibits low environmental loads and reduces a structural strength requirement of the wave energy conversion cylinder **100**.

Still referring to FIG. **2**, wave action of the water **202** causes a height of the water **202** to periodically change thereby causing alternating inclination of the wave energy conversion cylinder **100**. As the inclination of the wave energy conversion cylinder **100** changes, the bracket **108** and the magnet **112** move along the center rod **104** under the force of gravity. As the magnet **112** travels the length of the center rod **104**, the magnetic field produced by the magnet **112** induces an electric current in the plurality of electrically conductive windings **106**. An inclination angle produced by wave elevations is relatively invariant across sea states from mild to severe. Thus, the wave energy conversion cylinder **100** has an extended operating window from mild to severe sea states. Inclinations as low as approximately 1 degree can induce motion in the magnet **112** relative to the plurality of electrically conductive windings **106** and generate an electrical current. The light structure of wave energy conversion cylinder **100** allows the wave energy conversion cylinder **100** to operate throughout a full 360 degrees of pitch rotation in extreme survival sea states. As the sliding acceleration of the magnet **112** is induced by gravity, the relative velocity of the magnet **112**, which is proportional to motion-induced voltage, can be in larger scale than inertia-driven acceleration of other existing devices. In a typical embodiment the wave energy conversion cylinder **100** exhibits power conversion that is approximately 5 to approximately 10 times greater than acceleration due to inertia and, along with invariant wave inclination, makes the wave energy conversion cylinder highly efficient in short-crested seas.

FIG. **3** is a top view of a surface riding wave energy converter **300**. The surface riding wave energy converter **300** includes three wave energy conversion cylinders **100** arranged in a generally triangular configuration. A power umbilical **302** is connected to the wave energy conversion cylinders **100** so as to provide a connection for the surface riding wave energy converter **300** to a power grid or to an adjacent surface riding wave energy converter. In a typical embodiment, a tension element such as, for example, a hawser **304** is disposed with the power umbilical **302**. The hawser **304** bears tension loads resulting from wave action and prevents tension from being applied to the power umbilical **302**. In a typical embodiment, triangular arrangement of the wave energy conversion cylinders **100** facilitates alignment of the surface riding wave energy converter **300** with a direction of wave travel. Although the surface riding wave energy converter **300** is shown by way of example as having a triangular shape, the surface riding wave energy converter **300** may, in other embodiments, have a hexagonal, rectangular, or any other appropriate shape.

FIG. **4** is a top view of a surface riding wave energy conversion farm **400**. The surface riding wave energy conversion farm **400** includes a plurality of surface riding wave energy converters **300**. In a typical embodiment, the plurality of surface riding wave energy converters **300** are arranged in a triangular or "delta" configuration; however, in other embodiments, the surface riding wave energy converters **300** may be arranged in any pattern as dictated by design requirements. The surface riding wave energy conversion farm **400** is secured to, for example, a wind turbine platform **402** via a mooring **404**. In various embodiments, the wind turbine platform **402** can be a stand-alone platform or coupled to an existing wind farm. In other embodiments, the wind turbine platform **402** may be omitted. The surface riding wave energy conversion farm **400** is also connected to at least one concrete weight **408** or anchor. In a typical embodiment, connection of the surface riding wave energy conversion farm **400** to the mooring **404** and the at least one concrete weight **408** or anchor prevents drifting of the surface riding wave energy conversion farm **400** due to wave action. The surface riding wave energy converters **300** are arranged to facilitate accessibility for maintenance and repair. In a typical embodiment, the wave energy conversion farm **400** rides waves with negligible radiation waves and no significant disturbance to wave fields.

Still referring to FIG. **4**, an umbilical connection point **410** is associated with each surface riding wave energy converter **300**. As previously noted, the umbilical connection point **410** facilitates connection of the surface riding wave energy conversion farm **400** to, for example, a power grid. Additionally, the surface riding wave energy converters **300** are connected to each other via tethers **412**. The tethers **412** prevent the surface riding wave energy converters **300** from drifting apart due to wave action.

FIG. **5** is a top view of a hexagonal surface riding wave energy converter **500**. The surface riding wave energy converter **500** includes twelve wave energy conversion cylinders **100** arranged in a generally hexagonal configuration. A power umbilical **502** is connected to the wave energy conversion cylinders **100** so as to provide a connection for the surface riding wave energy converter **500** to a power grid or to an adjacent surface riding wave energy converter. In a typical embodiment, a tension element such as, for example, a hawser **504** is disposed with the power umbilical **502**. The hawser **504** bears tension loads resulting from wave action and prevents tension from being applied to the power umbilical **502**. In a typical embodiment, hexagonal arrangement of the wave energy conversion cylinders **100** facilitates alignment of the surface riding wave energy converter **500** with a direction of wave travel. Although the surface riding wave energy converter **500** is shown by way of example as having a hexagonal shape, the surface riding wave energy converter **500** may, in other embodiments, have a triangular or rectangular shape.

FIG. **6** is a top view of a surface riding wave energy conversion farm **600**. The surface riding wave energy conversion farm **600** includes a plurality of surface riding wave energy converters **500**. The surface riding wave energy converters **500** are arranged such that plurality of surface riding wave energy converters extend radially from a central buoy **602**. The surface riding wave energy converters **500** are connected to each other via the power umbilical **502** and the hawser **504** and are ultimately connected to the central buoy **602**. A central power umbilical **604** is connected to the central buoy **602** and provides connection of the surface riding wave energy conversion farm **600** to a power grid. Mooring lines **606** are connected to various ones of the surface riding wave energy converters **500**. In a typical embodiment, the mooring lines **606** prevent drifting of the surface riding wave energy conversion farm **600** due to wave action. The surface riding wave energy converters **500** are arranged to facilitate accessibility for maintenance and repair. In a typical embodiment, the wave energy conversion farm **600** rides waves with negligible radiation waves and no significant disturbance to wave fields.

FIG. **7** is a plan view of a tunable wave energy conversion cylinder **700**. The tunable wave energy conversion cylinder **700** includes an outer shell **702** and a center rod **704** disposed approximately along a length of a long axis of the outer shell **702**. A buoyancy shell **701** is disposed around the outer shell. In a typical embodiment, the buoyancy shell creates an air gap between the outer shell **702** and the buoyancy shell **701** so as to increase the buoyancy of the wave energy conversion cylinder. A plurality of electrically conductive windings **706** are formed about an inner circumference of the outer shell **702**. In a typical embodiment, the plurality of electrically conductive windings **706** are formed from an metallic material such as, for example, copper, aluminum, or steel; however, in other embodiments, any electrically conductive material could be utilized as dictated by design requirements. A magnet **712** is disposed on the center rod **704** such that the plurality of electrically conductive windings **706** are magnetically exposed to the magnet **712**. In various embodiments, the magnet **712** may be disposed on a bracket of the type described in FIG. **1**. In a typical embodiment, the magnet **712** is a permanent magnet; however, in other embodiments, various types of magnets such as, for example electromagnets could be utilized as dictated by design requirements.

Still referring to FIG. **7**, a first movable ring weight **720** and a second movable ring weight **722** are disposed between the outer shell **702** and the buoyancy shell **701**. In a typical embodiment, the first movable ring weight **720** and the second movable ring weight **722** are capable of longitudinal movement along an axis of the wave energy conversion cylinder **700**. In a typical embodiment, movement of the first movable ring weight **720** and the second movable ring weight **722** allows the wave energy conversion cylinder **700** to have active control to tune a mass moment of inertia of the wave energy conversion cylinder **700** for tilted angle motion. By utilizing a frequency measuring device, excitation frequency can be measured and the first movable ring weight **720** and the second movable ring weight **722** are adjusted to bring the natural frequency close to the excitation frequency. Such a matching of the natural frequency with the excitation frequency results in resonance that amplifies the sliding motion and power output of the wave energy conversion cylinder **700**. In a typical embodiment movement of the first movable ring weight **720** and the second movable ring weight **722** is actively controlled. An upper guide rod **703** and a lower guide rod **732** are installed through the first movable ring weight **720** and the second movable ring weight **722**. An interface of at least one of the upper guide rod **730** and the lower guide rod **732** with the first movable ring weight **720** is threaded. Likewise, an interface of at least one of the upper guide rod **730** and the lower guide rod **732** with the second movable ring weight **722** is threaded. By rotating at least one of the first guide rod **730** and the second guide rod **732**, the first movable ring weight **720** and the second movable ring weight **722** move along the screw thread.

FIG. **8** is a flow diagram of a process **800** for converting wave energy. The process begins at step **802**. At step **804**, a center rod is disposed along a length of an outer shell. At step **806**, a plurality of electrically-conductive windings are disposed around an interior circumference of the outer shell. At step **808**, a magnet is slidably disposed on the center rod. At step **810**, a power umbilical is electrically coupled to the plurality of electrically-conductive windings. At step **812**, the outer shell, containing the center rod, the magnet, and the plurality of electrically-conductive windings, are placed in a body of water as a wave energy converter. At step **814**, the wave energy converter is secured in place via, for example, mooring lines. At step **816**, the power umbilical is electrically coupled to a power grid. At step **818**, wave action in the body of water causes the magnet to move from along the center rod from end to end thereby inducing an electrical current in the plurality of electrically-conductive windings. At step **820**, the electrical current is transferred to the power grid via the power umbilical. The process **800** ends at step **822**.

Although various embodiments of the method and system of the present disclosure have been illustrated in the accompanying Drawings and described in the foregoing Specification, it will be understood that the disclosure is not limited to the embodiments disclosed, but is capable of numerous rearrangements, modifications, and substitutions without departing from the spirit and scope of the disclosure as set forth herein. It is intended that the Specification and examples be considered as illustrative only.

What is claimed is:

1. A wave energy conversion cylinder comprising:
an outer cylinder;
a center rod disposed along an axis of the outer cylinder;
a bracket slidably disposed on the center rod;
a plurality of electrically-conductive windings disposed about an inner circumference of the outer cylinder;
a magnet slidably disposed on the center rod; and
a buoyancy shell disposed outwardly of the outer cylinder.

2. The wave energy conversion cylinder of claim **1**, comprising:
a first moveable ring weight slidably disposed along the axis of the center rod; and
a second moveable ring weight slidably disposed along the axis of the center rod.

3. The wave energy conversion cylinder of claim **1**, wherein movement of the magnet along the center rod induces an electrical current in the plurality of electrically-conductive windings.

4. The wave energy conversion cylinder of claim **1**, comprising a plurality of bearing devices that facilitate movement of the bracket.

5. The wave energy conversion cylinder of claim **4**, wherein the plurality of bearing devices are ball rollers.

6. The wave energy conversion cylinder of claim **1**, wherein the magnet is coupled outwardly of the bracket.

7. The wave energy conversion cylinder of claim **1**, comprising an absorber block disposed at an end of the outer cylinder so as to dampen movement of the magnet.

8. The wave energy conversion cylinder of claim **1**, comprising a cable box disposed at an end of the outer cylinder, the cable box being electrically coupled to the plurality of electrically-conductive windings.

9. A wave-energy conversion farm comprising;

at least one wave energy conversion device, the at least one wave energy conversion device comprising at least one wave energy conversion cylinder, the at least one wave energy conversion cylinder comprising:

an outer cylinder;

a center rod disposed along an axis of the outer cylinder;

a bracket slidably disposed on the center rod;

a plurality of electrically-conductive windings disposed about an inner circumference of the outer cylinder;

a magnet slidably disposed on the center rod;

a buoyancy shell disposed outwardly of the outer cylinder; and

an umbilical electrically coupled to the plurality of electrically-conductive windings and electrically coupled to a power grid.

10. The wave-energy conversion farm of claim **9**, comprising at least one anchor coupled to the at least one wave energy conversion device.

11. The wave-energy conversion farm of claim **9**, wherein the at least one wave energy conversion device comprises three wave energy conversion cylinders arranged in a triangular pattern.

12. The wave-energy conversion farm of claim **9**, wherein the at least one wave energy conversion device comprises twelve wave energy conversion cylinders arranged in a hexagonal pattern.

13. A method of converting wave energy, the method comprising:

providing a wave energy conversion cylinder, the wave energy conversion cylinder comprising:

an outer cylinder;

a center rod disposed along an axis of the outer cylinder;

a bracket slidably disposed on the center rod;

a plurality of electrically-conductive windings disposed about an inner circumference of the outer cylinder;

a magnet slidably disposed on the center rod; and

a buoyancy cylinder disposed outwardly of the outer cylinder;

connecting the plurality of electrically-conductive windings to a power grid;

subjecting the wave energy conversion cylinder to wave action on a body of water; and

inducing an electrical current in the plurality of electrically-conductive windings responsive to movement of the magnet.

14. The method of claim **13**, comprising connecting a plurality of wave energy conversion cylinders together to form a wave energy conversion farm.

15. The method of claim **14**, comprising anchoring the wave energy conversion farm.

16. The method of claim **13**, comprising adjusting at least one of a first moveable ring weight and a second moveable ring weight.

17. The method of claim **16**, comprising tuning a mass moment of inertia of the wave energy conversion cylinder.

18. The method of claim **17**, wherein tuning the mass moment of inertia of the wave energy conversion cylinder comprises matching a natural frequency of the wave energy conversion cylinder with an excitation frequency.

19. The method of claim **16**, wherein a position of the first moveable ring weight and the second moveable ring weight are adjusted remotely.

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